

Article

Three-Dimensional Prospective Modeling and Deep Metallogenic Prediction of the Lintan Gold Deposit in Guizhou Province, China

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Abstract: The Lintan gold deposit, located in the “gold triangle” of Qianxinan, Guizhou Province, has become a focal point for implementing the “exploring near existing deposits” strategy, aiming to identify another large-scale gold deposit within the region. This study addresses the challenges of deep-edge mineral exploration in the Lintan gold deposit by adopting a metallogenic system perspective. Using a multidisciplinary approach, it integrates geological, geophysical, and geochemical datasets to construct various three-dimensional (3D) visualization and prospectivity models. The research leverages geostatistical theories and methods, multisource digital information analysis, and advanced 3D modeling and visualization techniques to verify mineralization anomalies. These efforts expand the scope of prospectivity evaluation for the deep-edge regions of the Lintan gold deposit into 3D space. In the 3D spatial framework, this study elucidates the metallogenic geological characteristics, geophysical anomalies, and geochemical signatures within the study area. Building upon this foundation, it conducts a comprehensive analysis and evaluation of geological, geochemical, and geophysical prospecting indicators under multisource geoscience datasets. This approach transitions from known to unknown domains, effectively reducing the ambiguities and uncertainties associated with single-source data interpretations. The findings demonstrate that, under the guidance of geological prospectivity models, the effective integration and synthesis of geological, geophysical, and geochemical data can reveal the interrelationships between metallogenic geological bodies and the contributing factors of the metallogenic system. This enables the identification of anomalous information associated with metallogenic geological bodies and facilitates the spatial localization and prediction of target areas for deep-edge mineral resources. The proposed methodology provides novel insights and techniques for deep-edge mineral exploration. Comprehensive analysis indicates significant prospectivity for mineral resource exploration in the deep-edge regions of the Lintan gold deposit.

Keywords: 3D geological modeling; metallogenic prediction; prospective modeling; Lintan gold deposit



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1. Introduction

Traditionally, two-dimensional (2D) geological maps have been widely used for mineral prospectivity prediction. These maps provide a straightforward representation of fundamental geological elements such as stratigraphy and structures, offering preliminary regional information for mineral exploration. They are cost-effective and relatively easy to acquire and interpret [1,2]. However, under the current trend of informationization and digitalization, 2D geological maps lack spatial depth information, making it challenging to accurately represent the morphology of complex geological bodies and the orientation

of mineral veins. With advancements in three-dimensional (3D) modeling technology, it has become possible to integrate multisource geological datasets, enabling a more precise visualization of geological structures. Furthermore, the integration of artificial intelligence and big data has introduced innovative methods to deeply merge geological models with mineral prospectivity data, enhancing predictive capabilities for exploration [2,3].

Finding hidden minerals is a worldwide challenge [4,5]. With the continuous extension of mineral exploration depth, the integration of geology, geophysics, geochemistry, and drilling technology continues to progress, and exploring for minerals in depth is also an inevitable trend [6–10]. The cross-fusion of new technologies such as big data, internet, and remote sensing with the mining industry and the research and application of digital, intelligent technologies and equipment have made the mining development increasingly strong [11,12]. Wang et al. [13] explore the multidisciplinary integration of the Fanggou molybdenum deposit and carry out big data mining of mine geological data. Zhou et al. [14] conducted a thematic study on integrating big data and geosciences; Bai et al. [15] carried out a three-dimensional prospecting prediction and evaluation of the Baiyanghe uranium deposit in Xinjiang Province.

With the development of mathematical geology, the digitalization, informatization, and three-dimensional visualization of mineral exploration are developing rapidly. Even through big data, the machine can carry out the deep prediction of artificial intelligence to look for minerals after in-depth learning. In this context, based on two-dimensional geological data, three-dimensional prediction methods for deep hidden ore bodies are emerging. The three-dimensional geological modeling technology integrating multiple disciplines such as geology, geophysics, geochemistry and structure provides a new approach for geological prospecting prediction. This technology intuitively displays geological structures, ore body distributions and geophysical and geochemical characteristics by constructing a three-dimensional underground geological model, and realizes comprehensive analysis of deep ore-forming conditions [11,16–20]. Cheng [21] established a geochemical model of 12 elements using 3D modeling technology and predicted the prospecting target area of the Zaozigou gold mine. Li [22] used 3D geological modeling means, based on the three-dimensional modeling and integrated mineralization prediction method of the mineral search geological model, to evaluate the direction of the deep search for gold deposits and mineralization potential of the early Zigou gold deposits; Yu et al. [23] used 3D model analysis to analyze the three-dimensional model of the Tieglongnan copper (gold) ore body in Tibet.

The Lintan gold deposit is located in the northwestern part of the Youjiang Basin, adjacent to the southwestern margin of the Yangtze Block. The mineralization occurred during the structural transition from Indosinian compression-orogenesis to Yanshanian extensional regimes [24]. The deposit exhibits metallogenic characteristics similar to Carlin-type gold deposits in the United States, while also displaying notable differences [25–29]. Structurally, the deposit is situated at the northern apex of a triangular zone formed by the northwest-trending Ceheng–Wangmo structure and the nearly north–south foreland-thrust system [30].

Based on the data of geology, tectonics, physical exploration, geochemistry, and profile of the Lannigou gold deposit area, this paper proposes a three-dimensional geological modeling and prediction method based on the theory of mineralization prediction, using three-dimensional visualization technology to express the spatial morphology and distribution characteristics of the geological body and mineralization body, analyze the interrelationships with the ore body, identify the anomalies of the mineralization body, and locate and predict the target area of the mineral resources in the deep border.

2. Geological Background

2.1. Overview of Regional Geology

The southwest Guizhou region is located on the southwestern edge of the Yangzi quasi-platform in the Nanpanjiang–Yuijiang foreland basin, west of the northern part of

the Yunnan–Guizhou–Guangxi “Golden Triangle” [31] (Figure 1). It is bounded by the Shizong–Mile fracture and the Yangzi Craton in the northwest, the Red River Shear Zone and the Simao Massif in the southwest, the Pingxiang–Nanning fracture and the Huaxia Palaeocontinent in the southeast, and the Ziyun–Yadu fracture and the Yangzi Craton in the northeast [32].

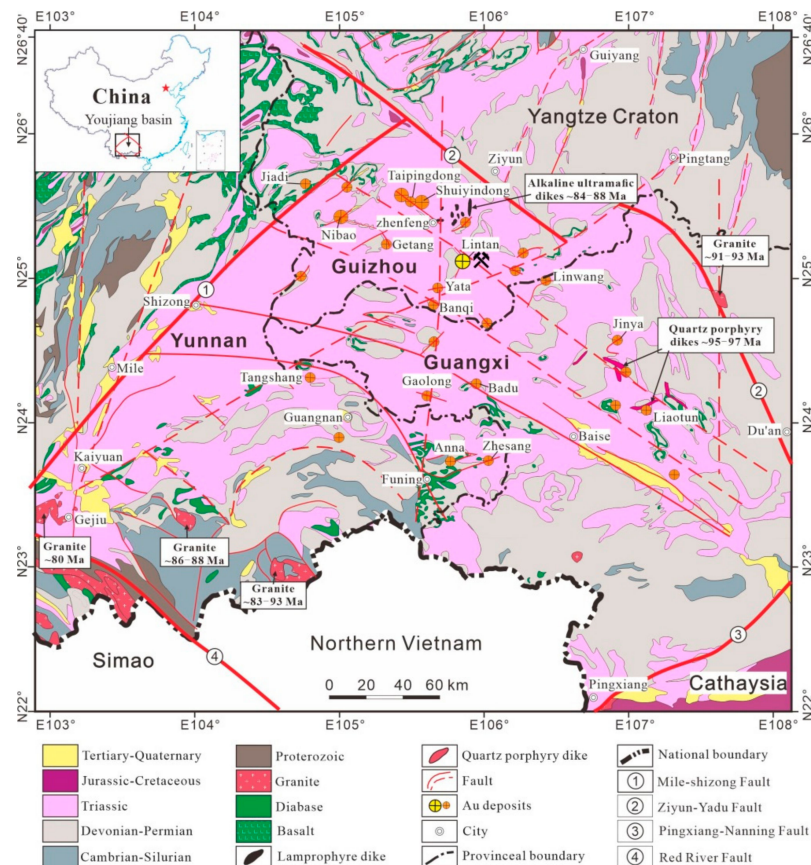


Figure 1. Geological map of the “Golden Triangle” region of Yunnan, Guizhou and Guangxi provinces [31].

Under the joint action of the tectonic dynamics of the two tectonic domains of the Littoral Pacific and the Tethys, the study area has experienced the evolutionary process of intra-tectonic rifting, extrusion, and uplift. In the early Neoproterozoic, the Yangzi Craton rifted, splitting the Yangzi Massif and the Huaxia Massif, and with the shrinkage of the South China Narrow Ocean Basin, a trench-arc-basin pattern appeared at the southeastern margin of the Yangzi Massif. From the Devonian, due to continental extension, the southern edge of the South China Plate was rifted, leading to the creation of the rift valley system in the region, controlled by the northwest- and northeast-oriented syn-sedimentary rupture, which resulted in the formation of rift valley and basement, “trough and platform” tectonic and paleogeographic patterns. Sedimentation continued until the Middle Triassic and the lithology is mainly sandstone, siltstone, and mudstone [32,33]. The Carboniferous-Permian is mainly a set of terrace-terrace margin shallow-water carbonates with a few deep-water basin clastic assemblages. The eastern part of the Early-Middle Triassic is a basin-marginal slope to a deep-water trough-basin depositional environment, which deposited thick deep-water gravity-flow and land-source clastic turbidites with high gold-bearing background values. In contrast, the western part of the area is mainly a set of carbonate rocks in a semi-confined terrace to terrace-marginal reef-beach phase. Magmatism in the area is weak, and magmatic rocks are exposed in a small area, mainly Permian continental overflow basalts and subducted volcanic phases of gabbro, belonging to the high-titanium ($\text{TiO}_2 > 2.8\%$) basalts in the eastern part of the Emei Mountain Great Igneous Province [34].

2.2. Geological Characteristics of the Deposit

The exposed strata in the mine area are mainly the Niluo and Bianyang Formations of the Middle Triassic Xuman Formation. The main lithology is deep-water basin-phase terrestrial clastic turbidites [24], the Bianyang Formation is dominated by grey thinly to medium-thickly bedded sandstones, plus a small amount of clayey siltstones, with the Bowmar sequence of B-C, B-D, A, D, and E layers, the Niluo Formation is dominated by grey-green thinly to medium-thickly bedded claystone and sandstones, and the Xuman Formation is dominated by grey to light-grey thinly to massive fine sandstones, with a small amount of claystone, and a small amount of claystone [24]. The Niluo Formation is dominated by gray-green thinly bedded to medium-thickly bedded claystone and sandstone, and the Xumang Formation is dominated by gray-light gray thinly bedded to massive fine sandstone, with a few calcareous claystone.

The tectonic structure of the mining area is mainly in the northwest direction, superimposed with northeast folds. The northwest folds often form a large-scale compound dorsal slope, constituting the main tectonic pattern of the mining area [24]. The northeast folds are small in scale and often modify the northwest folds. Lintan anticline is an inverted compound backslope, with an axial surface inclined to the northeast at 60° and a dip angle of about 55° . The core stratum consists of the Xuman Formation, and the outcrops on both flanks are the Xuman Formation, the Niluo Formation, and the Bianyang Formation in that order. The cutting of longitudinal fault F14 has damaged the anticline, and only the northwest end and the northeast wing are more intact. In the void space at the fracture and fold axis junction, silicification and limonitization are strong, and lens-shaped gold mineralization bodies are often formed. Currently, known gold ore is mainly produced on the Lintan anticline, lenticular output, controlling the maximum strike length of 240 m and the maximum depth of 374 m. The depth of the ore body is 55–355 m, and the elevation of the endowment is 163–460 m (Figure 2).

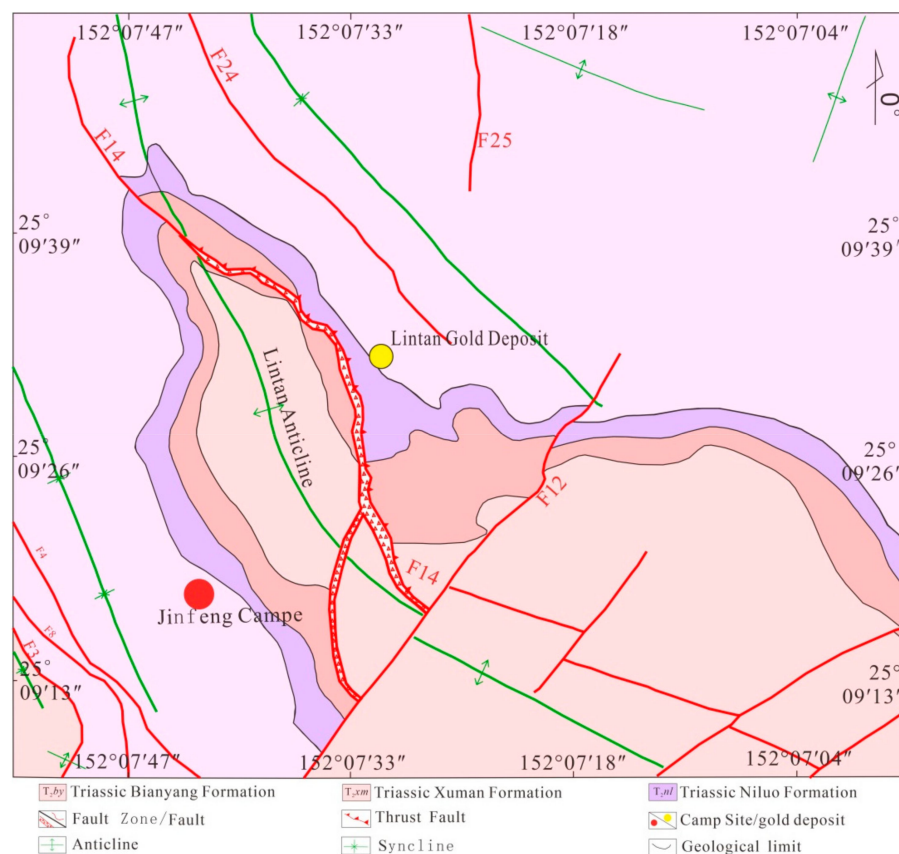


Figure 2. Geological map of the Lintan gold deposit.

3. Geological Modeling for 3D Visualization of the Mining Area

3.1. Modeling Method

This study used a combination of AutoCAD, Leapfrog, Mapgis, Geovia Surpac, and other software to complete the data processing and analysis for this study. Specifically, the original topographic AutoCAD format data collected from the mining area was used to edit and assign elevation using Geovia Surpac software 2021 X64; Geological modeling technology has been maturely applied in the field of geological exploration [12,35–39]. Li [40] used Surpac's two-dimensional geological block segment method to automatically estimate the resources; Dong et al. [41] studied the mineralization space of the Guilaizhuang gold mineralization area based on the data analysis function of Surpac software 2021 X64.

Contour data were re-edited and processed in Surpac, the fixed contour lines were assigned according to the spacing of 10 m, the cross lines were processed manually and layers cleaned up the duplicate points, and then the Geovia Surpac was used to create DTM model and fracture model; Finally, the results of assay analysis, stratigraphy, and fractures were interpreted in 3D using the mine database, and were analyzed using Leapfrog software 5.1. A total of 2 topographic and geological maps, 71 drill holes, and 2 geological exploration profiles were collected, and the data of the assay samples mainly contain five elements: Au, Ag, As, Hg, and Sb.

3.2. Three-Dimensional Stratigraphic, Tectonic, and Ore Body Modeling

Compared with the two-dimensional planar terrain contour, the three-dimensional DTM model can show the stratigraphy, structure, and other information more intuitively [35,42], Figure 3 is the three-dimensional stratigraphy, structure, and surface entity model of the Lintan gold deposit, from the figure can be read out intuitively, the terrain in the study area is cut larger, the central area and the northwest direction of the terrain is higher, the elevation of 710–830 m, and the east side of the study area and the southwest side of the area is relatively low, basically in the 350–400 m range. The terrain in the eastern and southwestern part of the study area is relatively low, basically between 350–470 m above sea level. To reveal the development of the fracture structure in the study area, the present study has established a three-dimensional fracture structure model by manually connecting the fracture zones with the geological information disclosed by the drill holes through the software to achieve the expected goal.

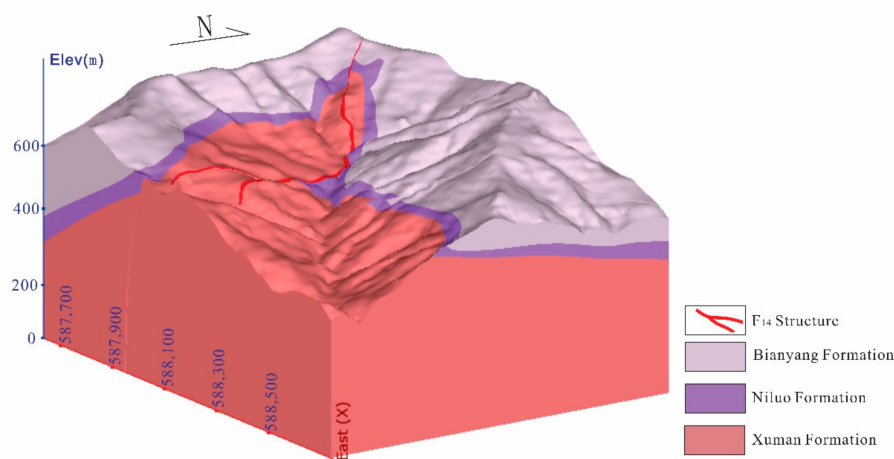


Figure 3. Schematic diagram of the three-dimensional model of topography and stratigraphy of the Lintan gold deposit.

3.3. Three-Dimensional Geochemical Modeling

Based on assay data from drill core samples, a three-dimensional spatial model focusing on Au elements was established. Initially, a mineralized domain model was constructed to represent the mineralized entity, ensuring the continuity of mineralization and alteration, which aligns more closely with the geological body's spatial occurrence. However, this

approach cannot reflect the distribution of mineralization intensity within the domain. To address this, a block model was developed on top of the entity model. The block model consists of uniformly shaped and sized blocks, with smaller blocks near the boundaries of the mineralized domain, typically set at half the size of the blocks within the domain. The volumetric difference between the block and entity models should be minimized.

The centroid of each block represents its corresponding spatial coordinates in 3D space. Using the actual grade data from drill holes, an inverse distance weighting (IDW) method from geostatistics was applied to interpolate grade values for each block. Each block thus obtained a corresponding grade value. Local validation of the block model grades was conducted by comparing the composite sample grades used in the estimation with adjacent block estimates and assessing extrapolation distances on section views. This evaluation ensured the scientific and reasonable nature of the grade estimates.

The block model parameters, such as block size, were determined based on the mine's actual exploration grid, the mineral body's spatial characteristics, and the interpreted understanding of the orebody. The basic block unit dimensions were set at $4\text{ m} \times 4\text{ m} \times 2\text{ m}$, with subdivided edge blocks at $2\text{ m} \times 2\text{ m} \times 1\text{ m}$. During estimation, a search ellipsoid was centered at the centroid of the mineralized domain. The shape of the ellipsoid was defined by the primary, secondary, and tertiary axes of the domain. Experimental variogram analysis guided the parameter settings, with the initial search radius set to match the basic drill spacing and the secondary search radius set to 1.2 times the initial spacing.

The Inverse Distance Power Law (IDW) method is a kind of interpolation statistics related to spatial distance.

When constructing a three-dimensional geochemical model, a geological information database was first established by organizing engineering data, basic analytical results, borehole deviation data, and lithological information. This process ensured that each engineering sample dataset was transformed into a three-dimensional dataset. Statistical analysis of the sample data revealed relatively uniform variation coefficients for the regionalized variables, with all coefficients $\leq 150\%$. This indicates that the use of the inverse distance weighting (IDW) method for grade estimation is appropriate and reasonable.

The grade-specific value is intercepted according to 97.5% of the sample data in all mineralized domains. At the same time, the samples are combined with the sample length, and a sample length of 1.0 m is uniformly used for the sample combination to reduce the bias that occurs in the valuation process. The 3D geochemical model is shown in Figure 4.

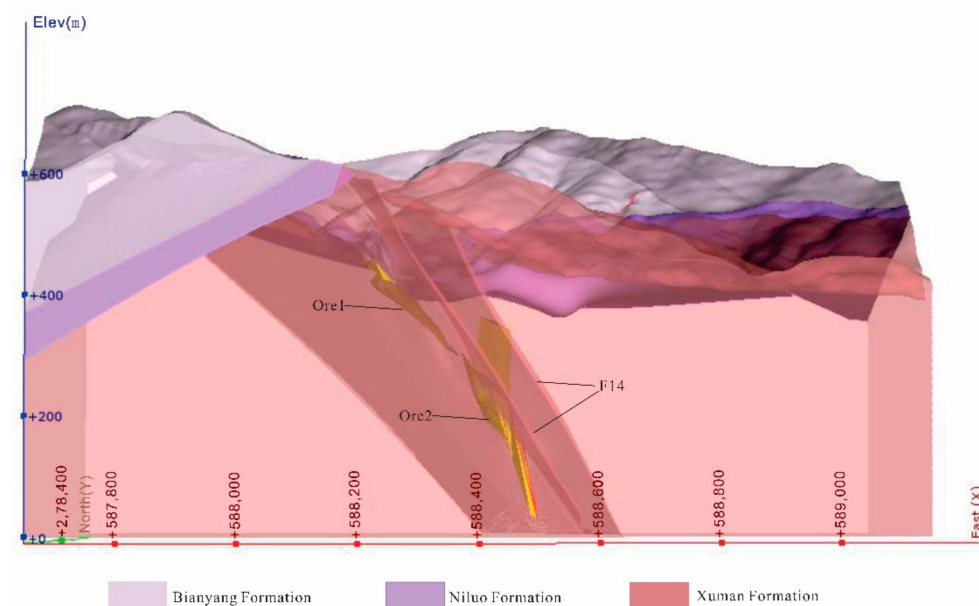


Figure 4. 3D spatial correlation model of Ore1, Ore2 bodies with stratigraphy and F14 in the Lintan gold deposit (gold ore bodies in yellow).

3.4. 3D Geophysical Modeling

The inference of the deep geological body information can be well shown by the 3D geophysical model [43–46], and exploration prediction can be conducted [47–50], CSAMT geophysical exploration technology can reveal the electrical characteristics of underground rocks, minerals, and fluids [51]. A CSAMT resistivity sounding survey was conducted in the eastern part of the study area, oriented perpendicular to the strike of the Lintan orebody. The survey line was 3320 m in length with an azimuth of 0° . The data acquisition equipment was the V8 multifunctional electrical workstation manufactured by Phoenix Geophysics, Toronto, ON, Canada.

The stratigraphic cover of the Xuman Formation and the Bianyang Formation in the area is relatively thin, and most of them are located above 0 m elevation. In the CSAMT inversion map, there are several deep anomalies in the area and one of them is a deep east–west-oriented fracture, which is presumed to be a right-trending fracture structure, which is faulted on the Lintan anticline, and then faulted by a northwest-oriented fracture structure in the later stage. Combined with geological data and drilling information, the Lintan gold ore is located in the high and low resistance contact zone and fracture tectonic zone, and the correspondence between the two is good (Figure 5).

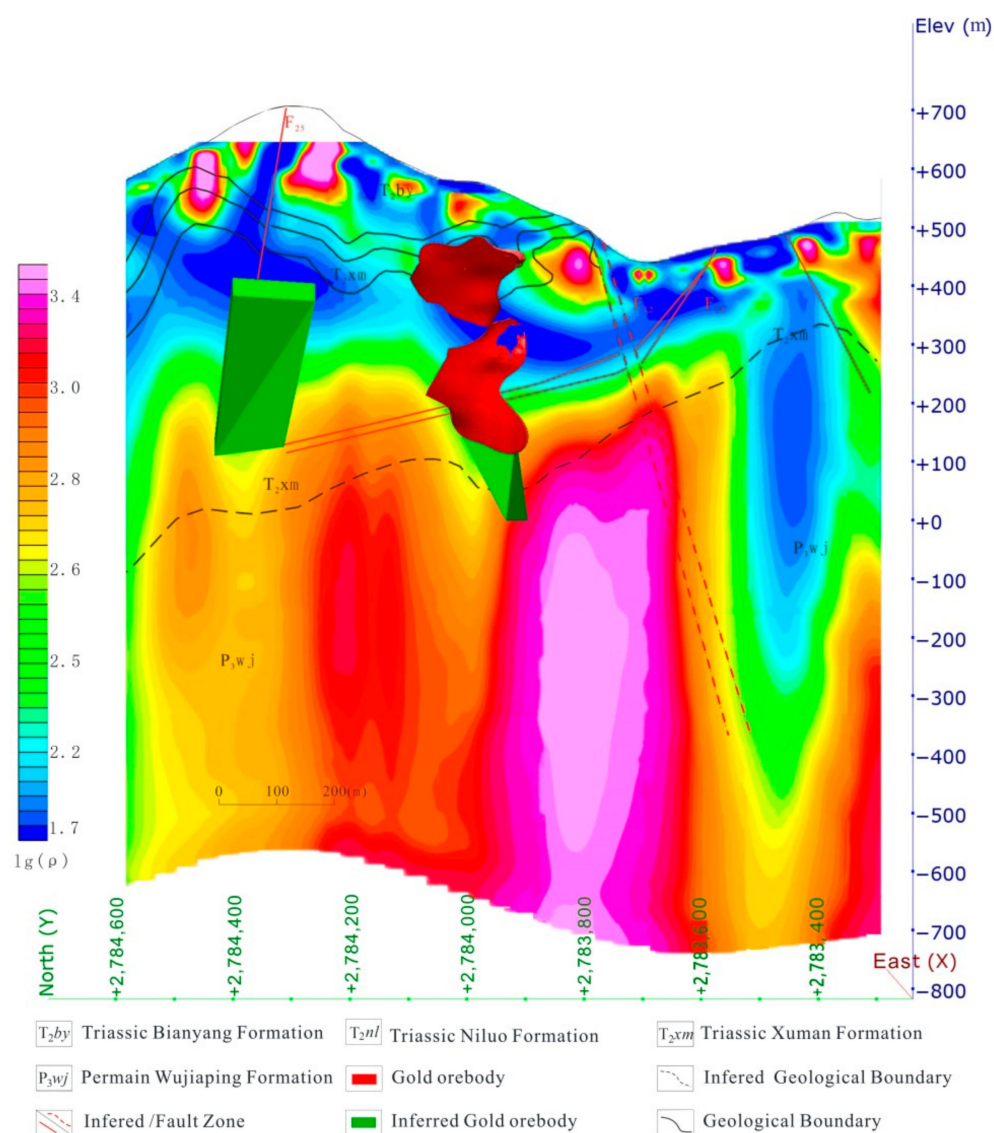


Figure 5. CSAMT subsurface topography with ore body and predicted ore body 3D spatial model for the Lintan gold deposit.

The geophysical exploration data collected in this study were processed using the conjugate gradient method. The inversion was performed utilizing the SCS2D software 3.4 package. The physical exploration geophysical model was established in three-dimensional space, and the three-dimensional space superimposed with geological, geochemical, and other ore-controlling factors for comparative analysis, which is used as the evaluation factor for the prediction of mineralization. Figure 5 shows the CSAMT geophysical survey results and ore body, etc., superimposed model recovered into three-dimensional space.

4. Geological–Geophysical–Geochemical Integrated Prediction

4.1. Establishing Predictive Models

The metallogenic system reflects the comprehensive processes and interactions of various factors contributing to ore deposit formation. The Lintan gold deposit, classified as a Carlin-type gold deposit, is primarily controlled by host rocks, high-angle structures, and low-temperature hydrothermal alteration. Thus, these ore-controlling factors are pivotal in constructing the prospectivity model.

The established prospectivity model focuses on three primary metallogenic factors: geology, geochemistry, and geophysics, tailored to the characteristics of the Lintan deposit. Geological factors are analyzed by investigating the relationships between ore bodies and structures, stratigraphy, and alteration zones. Geochemical analysis emphasizes the spatial distribution trends of Au grades and employs structural geochemical halo techniques. Geophysical exploration is utilized to test and analyze geo-electrical data at varying depths to infer subsurface lithological and geological information.

Based on a three-dimensional geological ore-finding model, a comprehensive method employing the “cubic predictive model” was used to conduct qualitative and quantitative analyses regarding the essential elements of the main ore-forming systems. This model aims to enhance predictive accuracy, reduce uncertainties associated with mineralization characteristics, and precisely locate potential mineral resources within a three-dimensional spatial framework [52,53]. This primarily includes ore-controlling factors, ore-forming geological conditions, and prospecting indicators. On this basis, a prospecting predictive model for the Lintan gold deposit was established, as shown in Table 1. The analysis of ore-controlling factors and ore-forming conditions mainly involves evaluating the mineralization of ore-bearing strata, controlling structures, and spatial mineralization within the orebodies. Geochemical model analysis primarily involves examining the concentration and spatial distribution characteristics using a modeled block of primary ore-forming elements. Geophysical model analysis involves the spatial distribution and geological interpretation of resistivity anomalies.

Table 1. Lintan gold ore search prediction model.

Mining Control Element	Predictors of Mineralization	Characteristic Variable	Analytical Methods
Geology	Tectonic, fracture zones	F14, F12 tectonic, and controlled by the Lintan anticline	Three-dimensional nested spatial relationships between alteration in situ space and ore-controlling structures
	Ore-bearing stratum	Slope-basin-phase carbonate and clastic depositional area of the Middle Triassic Xuman Formation to Bianyang Formation	Trend of ore body hosted lithology and grade concentration in three-dimensional spatial distribution
	Alteration zone	Pyrite mineralization, etc.	Interrelationships between ore bodies and alteration zones
Geochemistry	Single element exception	Spatial distribution of Au elemental grades	Calculation of trends in the spatial concentration and distribution of elements through geostatistical methods, as well as characteristics of the distribution of elements in geological survey profiles, and comprehensive comparative analysis and prediction with geophysical models
	Constructed stacked halos	Analyzing Au, Ag, As, Hg, Sb trends	Based on the method of tectonic geochemical study, analyze the near-mineral halo, tailing halo and other

Table 1. Cont.

Mining Control Element	Predictors of Mineralization	Characteristic Variable	Analytical Methods
Geophysics	CSAMT	Testing and analyzing ground power information at different depths	According to the information of geoelectricity at different depths, combined with the results of surface lithology, drilling holes, and physical characteristics, it is inferred that various types of high, medium, and low resistance body lithology or geological information

4.2. Ore-Forming Geological Conditions

Based on the 4 m × 4 m × 2 m basic block unit established in the study area, the number of basic blocks contained in different strata, structures, and alteration bodies was calculated separately from the centroid data of the ore body blocks. This computation aims to interpret the influence coefficient of a geological element on the mineralization process. The statistical results are shown in Table 2. The statistics reveal that the Byron Group stratum's cube of ore body grade model accounts for 2.17%. The mineralization rates for Au elements at ≥0.8 g/t and 2.2 g/t are 1.16% and 0.76%, respectively. The Niluo Formation's stratum cube of ore body grade model accounts for 3.84%. The mineralization rates for Au elements at ≥0.8 g/t and 2.2 g/t are 2.42% and 1.68%, respectively. The Xuman Formation's stratum cube of ore body grade model accounts for 93.99%. The mineralization rates for Au elements at ≥0.8 g/t and 2.2 g/t are 96.41% and 98.77%, respectively. This indicates that the Xuman Formation stratum is the most essential ore-bearing stratum in the area and is favorable for prospecting. The Bianyang Formation stratum has undergone more erosion, resulting in limited actual prospecting space, aligning with the current exploration situation.

Table 2. Ore-bearing rate of each metallogenic condition.

Ore Stratum	Cubic Number (math.)	Au ≥ 0.8 g/t Number of Blocks	Au ≥ 0.8 g/t Proportion (Ore Content %)	Mineralogy (%) (Au ≥ 0.8 g/t)	Au ≥ 2.2 g/t Number of Blocks	Au ≥ 2.2 g/t Proportion (Ore Content %)	Mineralogy (%) (Au ≥ 2.2 g/t)
ore body		167,965			92,470		
Xuman Formation	4109	1953	47.5298	1.1627	7	0.1704	0.0076
Niluo Formation	7246	4073	56.2103	2.4249	1126	15.5396	0.0168
Xuman Formation	177,464	161,939	91.2517	96.4123	91,337	51.4679	98.7747

Note: Mineralization = number of mineralized blocks in a certain ore-bearing stratum/total number of orebody blocks in that ore-bearing stratum × 100; grade of mineralization = number of mineralized blocks in a certain ore-bearing stratum/total number of orebody blocks in the study area × 100.

4.3. Geochemical Anomaly Information

Sample analysis data collected from drill holes were statistically processed in 1 m composite sample lengths. Then, a three-dimensional spatial distance power interpolation was performed to generate a three-dimensional distribution model of geochemical anomalies. This model provides an intuitive view of the spatial distribution characteristics of the primary ore-forming elements. Simultaneously, by using the software's sectioning function on the 3D geochemical anomaly model, spatial profile information from any direction and elevation was extracted. This further analysis aids in examining the variation in the distribution characteristics of the primary ore-forming element Au along the studied profiles. Simulation of ore body grade distribution based on assay data, Figure 6 reveals that the Au element gradually increases in grade towards the east–west direction at depth, with a reverse turn appearing around an elevation of approximately 150 m. Combining this with the geological exploration profile in Figure 7, it is inferred that this might be due to expansion and contraction caused by structural compression, and the mineralization along the exploration line towards the east has not completely closed off. Analysis of elevation data from all drill holes shows the presence of two mineralization enrichment zones, mainly distributed in the 500–400 m and 300–200 m intervals, with approximately 100 m of non-mineral space between them. Gold ore bodies often demonstrate pinching and swelling

features. Based on equidistant speculation, there is a further trend of extension in both structure and mineralization, Figure 8, suggesting a potential east–west extension of the ore body in the deep parts and a potential intersection between the northeastern F12 structure and F14 at depth in the southern part of the Lintan gold deposit. Therefore, based on the spatial variation analysis of grade across a series of profiles and the actual geological exploration in the mining area, it is speculated that there is potential for ore discovery along the trend of the Lintan ore segment towards the depth and northeast direction.

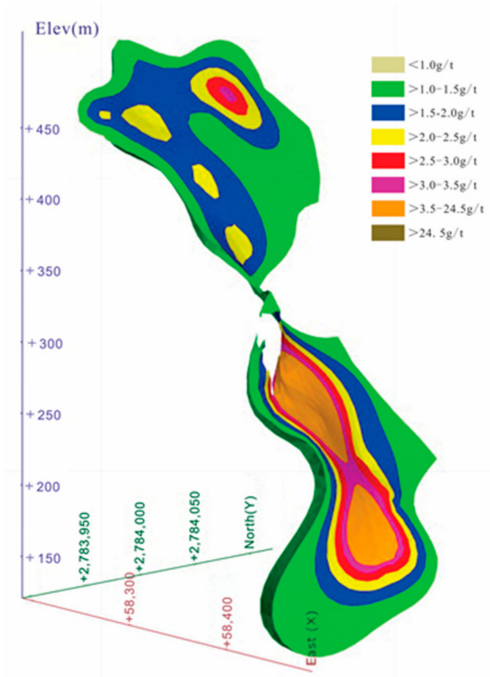


Figure 6. Simulated distribution map of Au element grades.

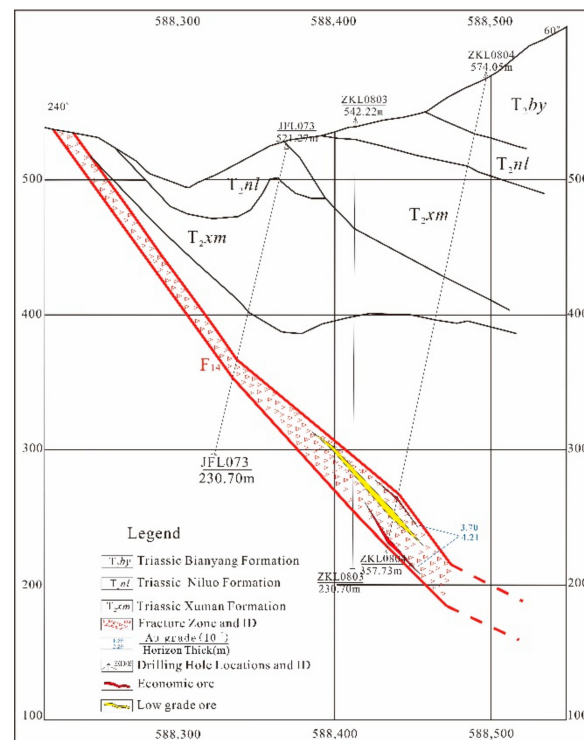


Figure 7. The profile of the No. 8 exploration line.

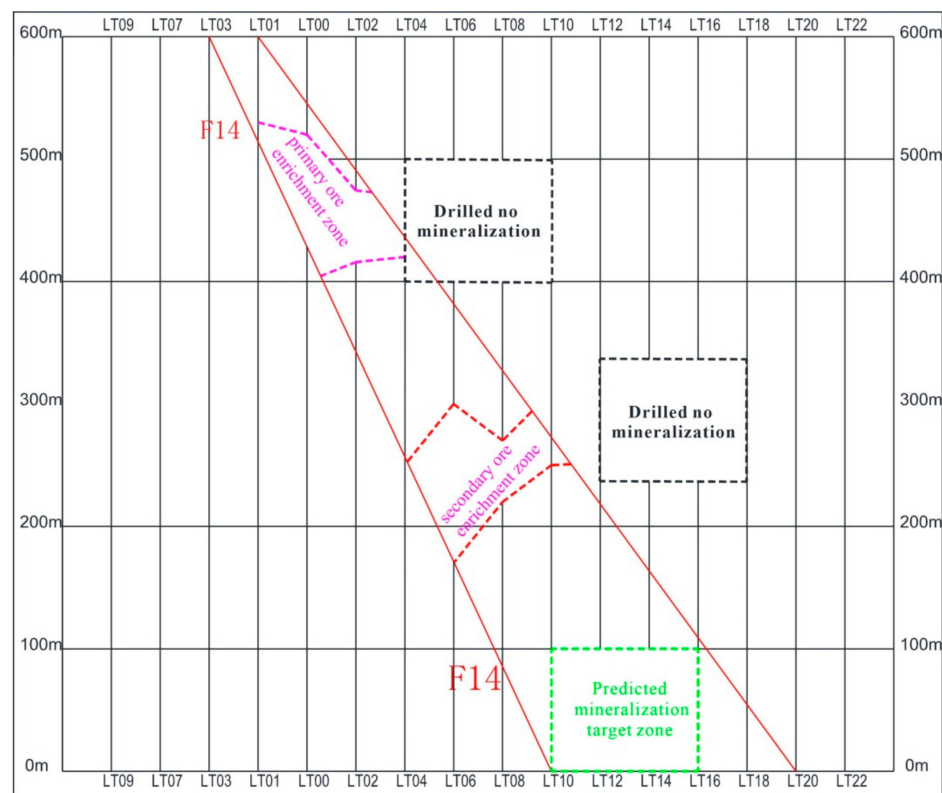


Figure 8. Trend prediction of the Lintan gold deposit.

4.4. Geophysical Anomaly Information

For areas with thick coverage and difficulty identifying surface outcrops, geological mapping and geochemical methods are insufficient to meet the exploration demands [54]. The CSAMT field equipment utilized in this survey included a V8 multifunction receiver, a TXU-30 transmitter, and a 30 kw generator. The survey employed an equatorial dipole measurement configuration, with the observation area arranged within a trapezoidal region defined by a 60° angle formed by the transmitting dipole. The upper base of the trapezoid corresponds to the position of the AB transmitting dipole. The distance RRR from the survey lines to the AB dipole was maintained at more than three times the skin depth. The length of the survey lines was confined within the trapezoidal area controlled by the 60° radiation of the transmitting dipole. The alignment of the AB dipole was designed to be parallel to the survey line direction, as per the survey requirements.

Vertically, from shallow to deep, the electrical resistivity varies from 1.8 to $2.8 \log(\rho)$, displaying a relatively regular pattern of low–medium–low–high resistivity, with distinct localized stratified features. Laterally, the resistivity shows considerable continuity. The impedance phase-frequency pseudo-section and the two-dimensional resistivity inversion section reveal the presence of a large area of medium- to low-resistivity bodies in the shallow subsurface along the profile.

According to surface lithology, borehole, and physical property analysis, these bodies are inferred to be fine sandstone, siltstone, and claystone, attributed to the Xuman Formation and Bianyang Formation. The resistivity parameters of different geological bodies are shown in Table 3. The deeper part of the profile exhibits a significantly thick high resistivity body, with substantial width, unenclosed at both the northern and southern ends and continuing downward. Based on physical characteristics, Limestone was encountered at a depth of 420 m in boreholes ZK171 of line 29, and the limestone exposure at a depth of 490 m in borehole JFL039 of line 4 at Lintan, this deep high-resistance body is inferred to be caused by limestone, as depicted in Figure 9. Leveraging the electrical differences

between ore and surrounding rocks, favorable sites for induced polarization anomalies can be outlined to analyze the scale and spatial positioning of subsurface polarized bodies.

Table 3. Resistivity parameters of different geological bodies.

Rock Type	Quantity	F(%)				$\rho(\Omega \cdot m)$				Electrical Characteristics
		Minimum Value	Maximum Value	Arithmetic Mean	Median	Minimum Value	Maximum Value	Geometric Mean	Median	
Bianyang Formation Mudstone	6	1.19	2.63	1.623	1.44	22.48	121.05	71.841	77.79	Low resistivity, low polarization
Bianyang Formation Sandstone	57	0.31	3.04	1.171	1.08	6.3	1617.22	244.927	256.97	
Ore	33	0.23	21.2	3.751	1.98	4.6	3273.28	445.348	635.26	Medium-low resistivity, high polarization
Luolou Formation Mudstone-Limestone	27	0.51	5.17	1.853	1.83	16.08	8905.71	888.776	954.45	High resistivity, medium polarization
Maokou Formation Limestone	35	0.11	7.28	1.081	0.48	400.61	22,851.38	3186.994	4224.35	High resistivity, low polarization
Wujiaping Formation Limestone	29	0.08	5.06	1.082	0.58	737.32	22,373.41	3555.245	3790.89	

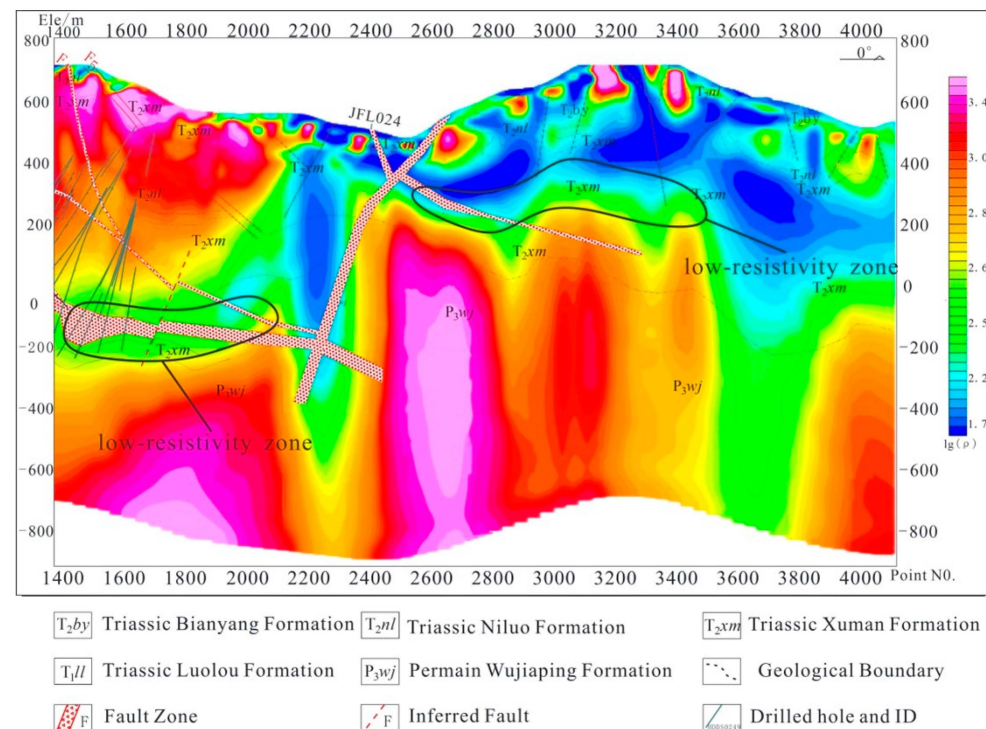


Figure 9. CSAMT resistivity 2D inversion section map.

At points 2320 and 3720 along the section, there are two nearly vertical longitudinal bands of low resistivity, penetrating the shallow Xuman Formation and Bianyang Formation and the deeper limestone formations. Considering the borehole control, it is believed that these two low-resistivity bands result from the influence of deep major faults, causing rock fragmentation, water ingress, and fault gouge.

Within 2.3–2.5 log(ρ) of the low-resistivity bands below points 1400 and 2600 along the section, the Lintan ore is present.

The following can be summarized: (1) The known shallow ore body locations within the area exhibit low-resistivity and high-amplitude frequency characteristics; (2) the deeper ore body locations are within band-like low-resistivity zones or at the high–low resistivity contact zones, where the low-resistivity bands or contact zones are controlling factors for mineralization structures.

4.5. Tectonic Geochemical Information

Tectonic geochemical studies primarily explore the relationship between tectonic activity and the migration and concentration of various geochemical elements, as well as the characteristics of ore-forming fluid migration [55–58]. Following intense gas–liquid activities, different tectonic systems will generate specific geochemical anomalies distinct from their surroundings [7,56,59,60].

The Carlin-type gold deposits in the southwestern Guizhou region are all located within the soil geochemical anomalies of the Au-As-Sb-Hg (TI) combination [60,61]. Compared to the surrounding rocks where tectonic development is absent, and mineralization information is weak, the geochemical anomalies (halos) in tectonically active areas are notably distinct with a steep gradient and best represent ore-induced anomalies [56,60]. Hence, deep-seated ore bodies can be linked to the mineralization halo at the surface along structures like faults and fractures, showing consistency and correlation. In recent years, the Institute of Geochemistry of the China Academy of Sciences has achieved significant exploration results using tectonic geochemical surveys in the periphery of Carlin-type Mercury Dongjin gold deposits. Gold deposits have been found in the Longtan Formation at depths exceeding 1000 m [31,60,62].

After analyzing the tectonic overlay halo characteristics of the Lintan gold deposit, the mean and standard deviation of each element were calculated. The original data were filtered with the “mean + standard deviation” as the upper limit and “mean – standard deviation” as the lower limit. After multiple filtering iterations, the optimal theoretical lower limit for each element was determined, set as the geometric mean of the element content plus twice the standard deviation. The values of 1, 2, and 4 times the abnormal lower limit were used as standards to define the outer, middle, and inner bands of element anomalies, as seen in Table 4.

Table 4. Statistical table of abnormal lower limits.

	Au	Ag	Co	Ni	Cu	Zn	Mo	Sb	W	Tl	Pb	Bi	Ba	As	Hg
Valid samples	635.0	428.0	375.0	226.0	307.0	250.0	526.0	615.0	469.0	305.0	316.0	311.0	372.0	667.0	585.0
average value	108.0	0.1	12.3	24.9	26.0	74.3	0.3	5.8	2.1	1.1	16.2	0.3	230.5	621.9	1971.6
Median	19.5	0.1	12.1	25.0	26.3	74.4	0.3	4.4	2.0	1.1	16.2	0.3	229.9	274.5	1301.9
standard deviation	193.6	0.0	1.3	1.7	3.3	4.6	0.1	4.6	0.4	0.1	2.4	0.0	36.5	709.3	1875.1
Minimum value	1.4	0.1	10.0	21.7	19.0	66.6	0.2	0.5	1.5	0.9	8.0	0.2	172.9	0.9	26.4
Maximum value	997.9	0.1	14.8	27.8	31.8	82.0	0.4	17.4	3.0	1.3	20.4	0.6	429.9	2596.0	6975.9
Mean + Standard Deviation	301.6	0.1	13.6	26.6	29.4	78.9	0.3	10.3	2.5	1.2	18.6	0.4	267.0	1331.2	3846.7
Mean – standard deviation	−85.6	0.1	10.9	23.1	22.7	69.8	0.2	1.2	1.7	1.0	13.8	0.3	194.0	−87.4	96.5
lower limit of the theoretical anomaly	495.1	0.1	15.0	28.4	32.7	83.5	0.4	14.9	2.9	1.3	21.1	0.4	303.5	2040.4	5721.8
Practical Abnormalities of the Outer Girdle	500.0	0.1	15.0	28.4	32.7	83.5	0.4	14.9	2.9	1.3	21.1	0.4	303.5	2040.4	5721.8
abnormal in practicality	1000.0	0.2	30.0	56.8	65.3	167.0	0.8	29.8	5.9	2.7	42.2	0.8	607.1	4080.9	11,443
Practical internal band anomalies	2000.0	0.4	60.0	113.5	130.7	334.0	1.5	59.6	11.8	5.3	84.3	1.6	1214.	8161.7	22,887

Unit: ppb.

Based on the vertical profile of the tectonic overlay halo for each element, taking the LT02 exploration line as an example, the tectonic overlay halo characteristics are as follows: The Au element primarily exhibits inner-middle-outer band anomalies, with a larger overall area of inner-band anomalies that extend further into the deep. The Ag element mainly displays outer band anomalies, while the middle band anomalies show a narrower strip-like distribution, Figure 10.

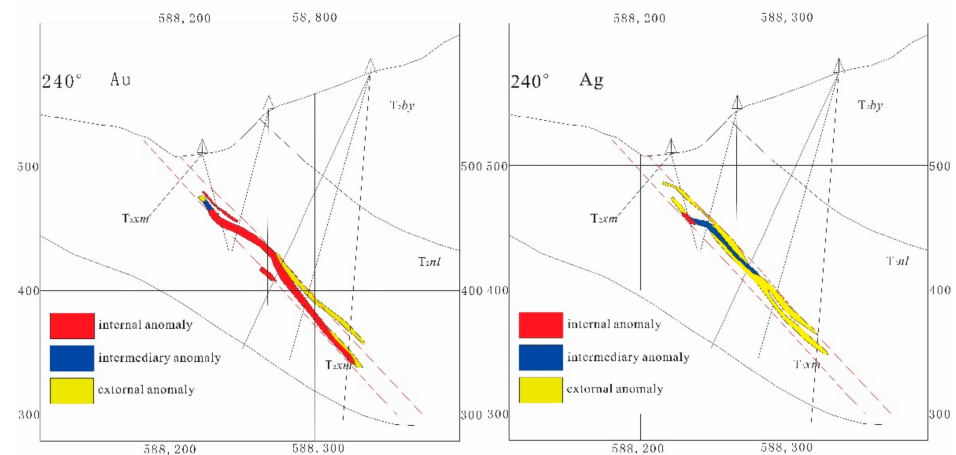


Figure 10. Au and Ag anomaly profiles of exploration line LT02.

The As element anomaly primarily exhibits an inner-middle-outer band anomaly. The inner band anomaly is not closed and extends considerably on both sides. The Sb element primarily displays a middle-outer-inner band anomaly. The middle band anomaly has a relatively large scale and extends far on both sides; the middle-inner band undergoes annihilation in the deeper sections. Refer to Figure 11. The Hg element shows an outer-middle-inner band anomaly. The outer band anomaly is relatively strong, the middle-inner band anomaly does not extend far, and experiences annihilation at the 400 m elevation, as shown in Figure 12.

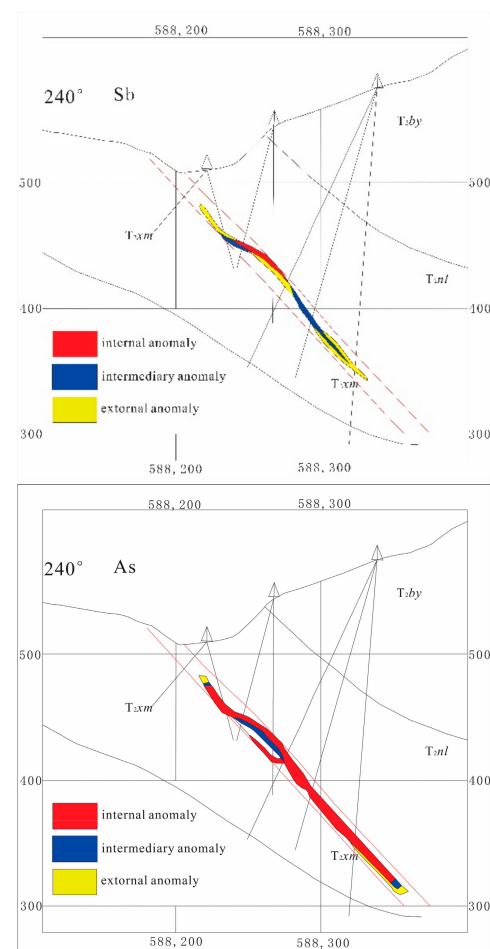


Figure 11. As and Sb anomaly profiles of exploration line LT02.

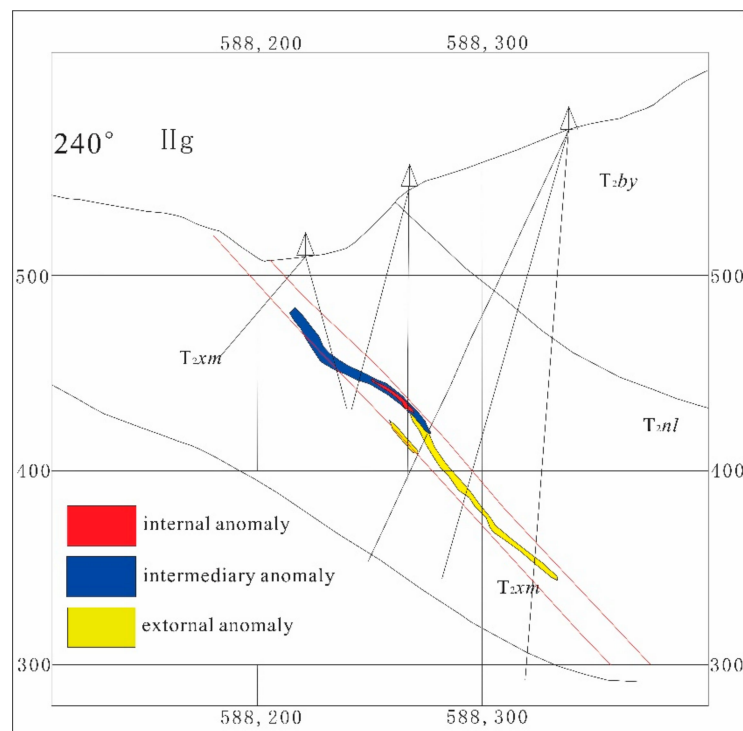


Figure 12. Hg anomaly profile of exploration line LT02.

The above observations lead to the conclusion that the Lintan gold deposit showcases a strong inner band anomaly near the ore halo tail. The front edge of the halo is primarily characterized by inner-middle-outer band anomalies, with the inner band anomaly being particularly intense. The tail of the halo mainly exhibits outer band anomalies, while in the deeper sections at the 400 m elevation, some indicator elements display middle band anomalies. Therefore, the Lintan gold deposit features a strong near-ore halo, a robust frontal halo, and a relatively weaker tail halo. The predicted optimal mining location is the middle part of the ore body, with significant extensions observed towards the deeper sections.

4.6. Integrated Prediction and Deep Prospecting Analysis

An analysis of the distribution characteristics of geochemical element anomalies reveals a gradual enrichment trend and an increase in gold element grade from shallow to deep in the east–west-, northwest–southeast-, and northeast–southwest-oriented block models as well as in exploration profiles. Additionally, there's a possibility of grade escalation within the ore body, indicating a potential resurgence. Surface soil geochemistry exploration demonstrates that Hg and As element anomalies generally trend in a northwest–southeast direction, consistent with the orientation of the F14 fault line. The As anomaly displays characteristics along the Lintan anticline distribution, although relatively weaker anomalies are observed in the eastern region. Combining the analysis of tectonic geochemical halos, it is inferred that the mineralized structure inclination, burial depth, and erosion levels may be related. Additionally, it is suggested that the mineralized structure in the deeper sections might intersect with the northeast-oriented fault F12, with the deeper ore bodies relatively more deeply buried towards the western region.

Recent research has found the presence of a suite of deep gray, moderately silicified limestone and conglomeratic claystone formed by the combined action of sedimentation, tectonics, and hydrothermal alteration between the Permian (P) and Triassic (T) in the southwestern Guizhou region, known as the SBT mineralization model [62]. Comprehensive analysis of the CSAMT geophysical interpretation results and the known ore body models indicates that the gold ore body is distributed within a resistivity range of 1.7–2.5 log(ρ).

This resistivity range may correspond to the P/T interface of the controlling geological structure, which aligns with the current exploration criteria for the SBT model in the Qian-nan region. The structural features F14, F25, and their parallel alignments with the main mineralized structures F70 and F3 in the Lannigou mining area indicate a predominant thrusting movement during orogeny, evolving into dominant normal slip or right-lateral movement in the later stages [24]. Moreover, near the Laizi mountain anticline, significant uplift of the ore body occurs, experiencing extensive erosion, deeper structuring towards the east, and deeper ore bodies towards the western area, constituting a characteristic imbricated structure. The low-resistivity anomaly zone detected in the geophysical survey reflects the presence of metallogenic potential in the deep eastern side and northeastern direction of the Lintan anticline.

Through drilling verification, it was found that at an elevation of approximately 175 m in the Xuman Formation, a mineralization phenomenon of 0.28 g/t was discovered within a fractured structural zone, possibly indicating a positive fault structure. Additionally, at an elevation of 960 m, a 0.33 g/t mineralization anomaly was observed in the silicified limestone area. These anomalies confirm the potential existence of mineralized bodies in the deeper regions of the mining area, as depicted in Figure 13.

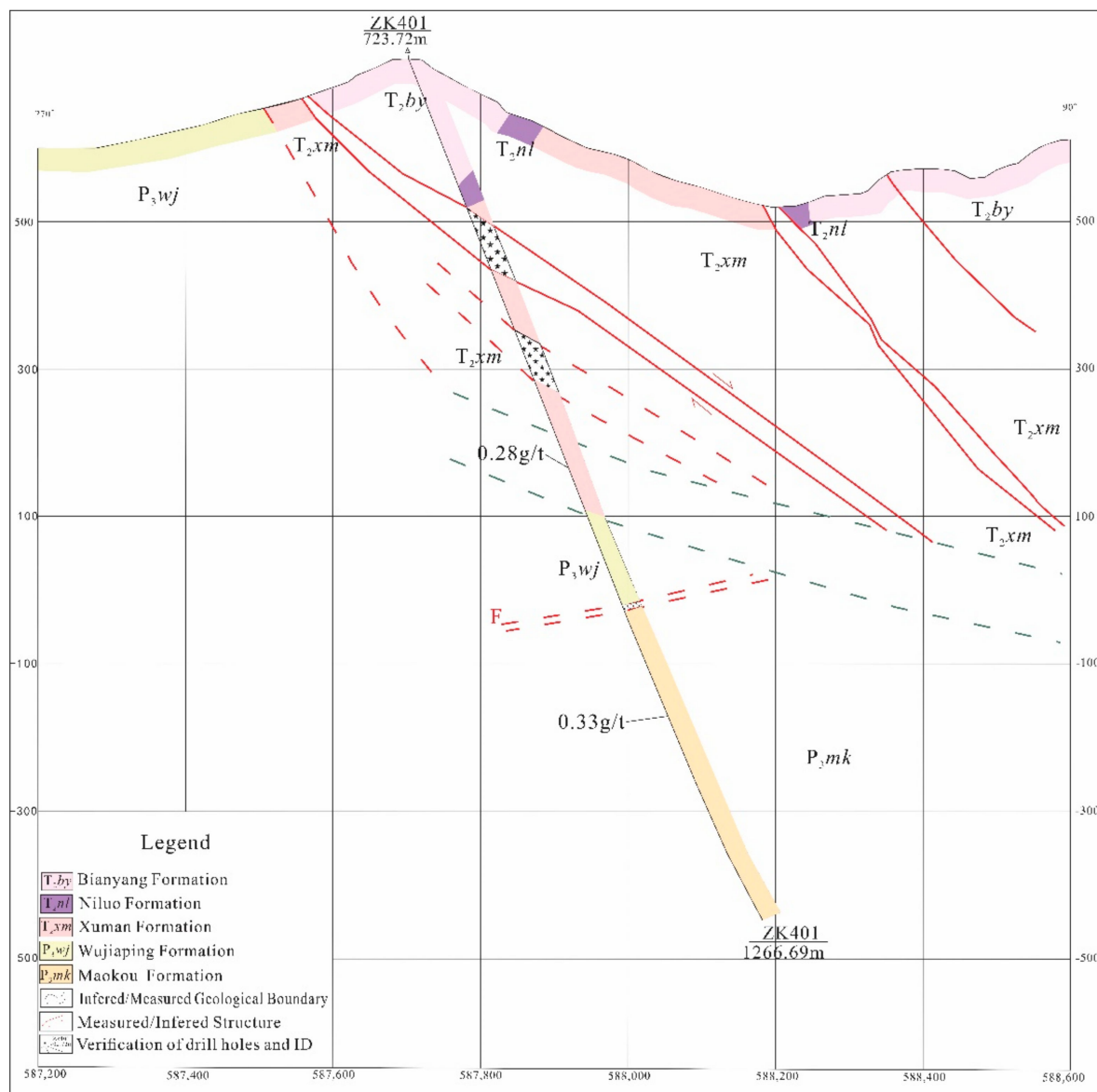


Figure 13. Drill verification profile of line 04.

In summary of the above analysis, utilizing the known to infer the unknown in the CSAMT resistivity 2D inversion model, two potential mineralization positions have been hypothesized—namely, the intersection positions of the ore body extension structures or the intersection positions corresponding to the induced polarization and grade block model trend anomalies, as depicted in Figure 5.

5. Conclusions

- (1) The 3D geological model allows for the intuitive analysis of the spatial relationships between ore bodies and various metallogenic system elements, particularly their contact and associations with strata and structures. The primary ore-grade model distinctly interprets the concentration and distribution trends of grade variations in 3D space. Combined with structural geochemical halos, it provides further insights into the spatial distribution patterns of ore bodies. The 3D geological modeling of the Lintan gold deposit reveals that the ore bodies are primarily hosted within the Xuman Formation and are strictly controlled by the Lintan anticline and the F14 structure.
- (2) By establishing an exploration model, geological metallogenic conditions, geochemical signatures, and geophysical indicators can be analyzed in 3D space, enabling the identification of commonalities for metallogenic prediction and evaluation. This approach reduces the ambiguity and uncertainty of relying on single-source data. Comprehensive analysis indicates that the Lintan gold deposit is strictly controlled by the F14 structure, with high-grade Au blocks displaying upward enrichment trends in two spatial directions, which are presumed to be closely related to the F25 and F12 structures within the region. The CSAMT low-resistivity zone also demonstrates a strong spatial correspondence between the F14 structure and the known ore bodies. Additionally, the deep low-resistivity anomaly zone provides geophysical indicators for further exploration in the deeper peripheral regions.
- (3) Based on the integrated 3D geological model, geochemical element model, geophysical model, and the comprehensive analysis of geological–geochemical–geophysical exploration information, it is concluded that the Lintan gold deposit exhibits exploration potential in the near east–west trending deep zones and in the northeastern direction.

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